A Multi-Scale Elasto-hydrodynamic Contact Model of Chemical Mechanical Planarization

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CMP is an enabling technology for planarizing metal and interlayer dielectric (ILD) layers that form the multilevel interconnections between IC devices. However, CMP mechanisms have not been well enough understood to predict process responses from tool design and consumables specifications; to determine efficient operating conditions. In this paper, we present a physically based multi-scale finite element model to help better understand CMP process. We extend a model that is presented in Ref. 1. The extended "soft" elasto-hydrodynamic contact model captures the fundamental mechanical aspects of CMP process. The physically based model requires few *ad hoc* assumptions or adjustable parameters.

For a given global normal downforce and frequency distribution function of asperity heights, some pad asperity tips do not touch the opposing wafer surface, others barely touch and are slightly deformed, and others are severely deformed. The strains for a well-deformed asperity are certainly not the small strains required by linear elastic theory. The constitutive equation for the polymer pad material must be some form of large strain nonlinear elasticity, such as hyperelasticity [2]. A physically based asperity-scale hyperelastic model is presented to calculate local stresses at asperity tips that are directly related to most widely accepted material removal models. The model includes a frictional effect.

There have been two distinct explanations of the mode of material removal during CMP. One suggests that the workpiece is separated from the polishing pad by a hydrodynamic film of slurry, and polishing is done by collision of the abrasive particles with the surface (erosion). The other suggestion is that the wafer contacts pad asperities and material is removed due to relative rubbing motion of two bodies with entrained abrasive particles (abrasion). For the latter model (abrasion), any contribution due to erosion is believed to be minor.

When a fluid-lubricated journal bearing is operating, a change of friction coefficient can be monitored to determine the contact status at the lubricated interface. If the shaft is fully supported by a thin lubricating fluid, then the coefficient of friction should increase with the applied load. However, if the contact mode is elasto-hydrodynamic; i.e., mixed direct solid-solid contact and partial fluid lubrication, then the friction coefficient decreases with the applied load, [3]. Most recent experimental results show that the friction coefficients in CMP processes decrease as the applied load increases [1, 4-5]. Fluid suction pressures are also routinely observed, which is also evidence for elasto-hydrodynamic lubrication. The experimental and theoretical results presented in this paper support elasto-hydrodynamic contact (abrasion) at the pad-wafer interface.

Solid contact pressures are calculated using the commercial finite element analysis program ANSYS. The equivalent fluid film thickness then can be calculated by using a modified Greenwood-Williamson (GW) statistical contact model [6] for curved surfaces with hyperelastic asperities. The fluid is assumed to flow through a film of varying height, which is essentially the effective height of the compressed asperities. Assuming a continuous fluid flow at the interface, the Reynolds equation of hydrodynamic lubrication can be used to calculate the interfacial fluid pressures [7]. The channel height that is calculated using a modified GW model is used to define a Reynolds' flow analysis in ANSYS.

In most CMP tools, the external downward force is applied to the wafer-carrier head through a ball joint, which in principle cannot transmit a moment. In order to obtain closure of the analysis, the mean depth into the pad and tilt angle of the wafer are determined by the normal global force applied and momentum balances using the Levenberg-Marquardt method [8].

Finally, we summarize our approach to linking the asperity scale contact analysis to the wafer scale model through a statistical method [9].

REFERENCES

1. J. A. Tichy, J. Levert, L. Shan and S. Danyluk, **J. Electrochem. Soc. 146(4),** 1523 (1999).
2. Lai, W.M., D. Rubin and E. Krempl, *Continuum Mechanics*, 3rd Ed., Pergamon (1993).
3. J. A. Williams, *Engineering Tribology*, Oxford Science Publication (1994)
4. L. Shan, Ph.D. Thesis, Georgia Institute of Technology, 2000.
5. Y. Moon, D. Dornfeld, Procedings of American Society for Precision Engineers (ASPE), vol. 18, pp.591-596, 1998 Annual Conference.
6. J. A. Greenwood and J. B. P. Williamson , **Proc. Roy. Soc. London**, A295, 300 (1966).
7. B. J. Hamrock, *Fundamentals of Fluid Film Lubrication*, McGraw-Hill, (1994).
8. W. H., Press, S. A., Teukolsky, W. T. Vetterling, B. P. *Flannery, Numerical Recipes in Fortran*, Cambridge (1996)
9. T. R. Thomas, *Rough Surfaces*, Longman, (1982).